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Mélanges and olistostromes in the Puerto Plata area (northern Dominican Republic) as a record of subduction and collisional processes between the Caribbean and North-American plates

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ABSTRACT

The Cordillera Septentrional records the oblique subduction and collisional processes between the Caribbean and North American plates during Late Cretaceous to early Palaeogene times. The Puerto Plata basement complex of this range is considered to represent a fragment of the frontal part of the Great Arc of the Caribbean in Hispaniola that originated during thrusting of the Caribbean plate onto the North American shelf. This paper describes and interprets mélange-type formations spatially related to this basement complex and its associated sedimentary cover, the Imbert Fm. Such formations include the San Marcos olistostromic Fm and a unit of Serpentinic Breccias located at the base and interbedded in the lower section of the former. Both units are Eocene in age, have been mainly deposited by syntectonic subaqueous mass-transport processes and typically host a varied mixture of blocks of known and unknown origin, including high-P metamorphic rocks (knockers). Cartoon models of palaeotectonic reconstructions depicting the final stages of subduction and the onset of collisional process in Early and Middle Eocene times respectively, are proposed in order to show the original relationships among all geological units involved in the study area. The Serpentinic Breccias are interpreted as being the result of extensive sedimentary recycling of peridotite and serpentinite massive bodies or subduction related mélanges when exposed at the surface by return flow during early exhumation stages of the accretionary complex, coevally with the end of island-arc volcanism. This process is inferred to be the triggering mechanism for the feeding of originally deep-sited knockers, probably in combination with strike-slip tectonics and associated mud diapirism The slightly younger San Marcos Fm records the collision event and main exhumation stage, while displaying the typical features present in olistostromes and other mass-wasting, gravitationally-driven deposits recognized in extensive areas of forearc and accretionary complexes involved in arc-continent collisional processes.

1. Introduction

Over the last years, several publications about mélanges, olistostromes and other related 'chaotic' formations (e.g. broken formation, block-in-matrix rocks, argille scagliose, tectonosomes, mud volcanoes, etc.) have provided a review of the historical evolution of these terms as well as a general background for the characterization of these "widely-extended" formations around the world (e.g. Camerlenghi and Pini, 2009 and Festa et al., 2010a; 2010b). The participation of different processes (e.g. tectonic, sedimentary, diapiric and interrelated) or the influence of high fluid pressures are well known subjects related to the creation of these mélange-type units and their combined effects have been discussed as causes (amongst others) for their disorganized internal fabric (e. g. Aalto, 1981; Cowan, 1985; Needham, 1995; Page, 1978; Pini, 1999; Rast and Horton, 1989; Raymond, 1984). Currently, new concepts and classifications are continuously being brought forward in order to advance in the knowledge surrounding these units, focusing primarily on the distinction of melange-forming processes under different tectonic or geodynamic scenarios, as in the case of collisional and accretionary orogenic belts (Chang et al., 2001; Harris et al., 2009; Moore and Byrne, 1987; Orr et al., 1991; Pollock, 1989; Ujiie, 2002; Yamamoto et al., 2009). Meanwhile, the classic discussion about the tectonic or sedimentary origin of mélanges is still alive (Burg et al., 2008;

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Robertson, 2004), even in the case of emblematic and well studied mélange formations such as the assemblages of the Franciscan Complex (Cloos, 1984; Cowan, 1985; Wakabayashi, 2011).

Mélange is a multi-use term that has been applied to any kind of internally chaotic formation showing a "block-in-matrix" fabric, which may or may not include ophiolitic rock assemblages. The term olistostrome is more commonly used to describe mélange-type units of clear sedimentary origin (Festa et al., 2010b). Mélanges containing exclusively (or mostly) ophiolitic assemblages and including high (HP) or ultrahigh (UHP) pressure metamorphic rocks (typically blueschists and eclogites embedded in serpentinite matrices) are common elements in continental subduction contexts, and have been associated with exhumed portions of the subduction channel or the accretionary prism of the collisional orogen. The study of P-T-t paths followed by the HP or UHP rocks provide invaluable information on the burial and exhumation history of subducted and accreted rocks, and therefore on the whole evolution of the orogeny itself (Agard et al., 2009; Guillot et al., 2009, and compilations therein). However, HP metamorphic rocks have also been found as exotic blocks (formerly named knockers by Karig, 1980) within sedimentary or, in general, clay-matrix mélanges, far away from their most plausible genetic setting. In this case, different mechanisms for deep-sited feeding of these blocks have been proposed, principally involving return flow models (Cloos, 1982; Cloos and Shreve, 1988a, 1988b; Gerya et al., 2002), but also strike-slip tectonics either combining or not combining mud diapirism (Fryer et al., 1999; Karig, 1980).

Mélanges and olistostromes are concepts that have been used to describe, define or interpret rocks and formations outcropping in basement complexes of the Cordillera Septentrional in the Dominican Republic (Fig. 1). This range, together with the Samaná Peninsula, record the (oblique) subduction and collisional processes between the Caribbean and North American plates during Late Cretaceous to early Palaeogene times, prior to the onset in Late Eocene times of an intense, transpressive deformation episode in a left-lateral strike-slip context that has continued until present. Recent geochronological dating of the onset of (continuous, south-dipping) subduction between these two plates has yielded an age of about 120 Ma (Krebs et al., 2008), which fits well with regional considerations (Pindell et al., 2005). The basement complexes of the Cordillera Septentrional are considered to represent fragments of the island arc, the forearc or the accretionary wedge (cf. Moores and Twiss, 1995) originated during NE-directed thrusting of the Caribbean plate onto the North American shelf at the western continuation of the Puerto Rico trench (North Caribbean deformed belt; cf. Dolan et al, 1998; Fig. 1), which were subject to shearing and lateral displacement during subsequent strike-slip faulting (de Zoeten and Mann, 1999; Draper and Nagle, 1991; Joyce, 1991; Pindell and Draper, 1991).

In the Samaná Peninsula, the Samaná accretionary complex consists of an imbricate stack of several discrete high-P nappes resulting from the underplating of the subducting North American carbonate platform margin and related pelagic sediments (Escuder-Viruete and Pérez-Estaún, 2006; Joyce, 1991). A big T and P jump exists between the uppermost Majagual-Los Cacaos unit and the underlying main pile of sheets, which are arranged in an inverse metamorphic sequence that culminates in the marbles, calcschists and micaschists of eclogite and blueschist facies belonging to the Punta Balandra nappe. This unit includes in its upper levels a 35 m thick ophiolitic mélange composed of mafic and ultramafic blocks wrapped in a serpentinite or metapelitic schistose matrix (Escuder-Viruete, 2008; Escuder-Viruete et al., 2011). Below the Punta Balandra unit, the structural pile is completed (in descending order) by the Santa Bárbara Schists, El Rincón Marbles and Playa Colorada Phillyte nappes.

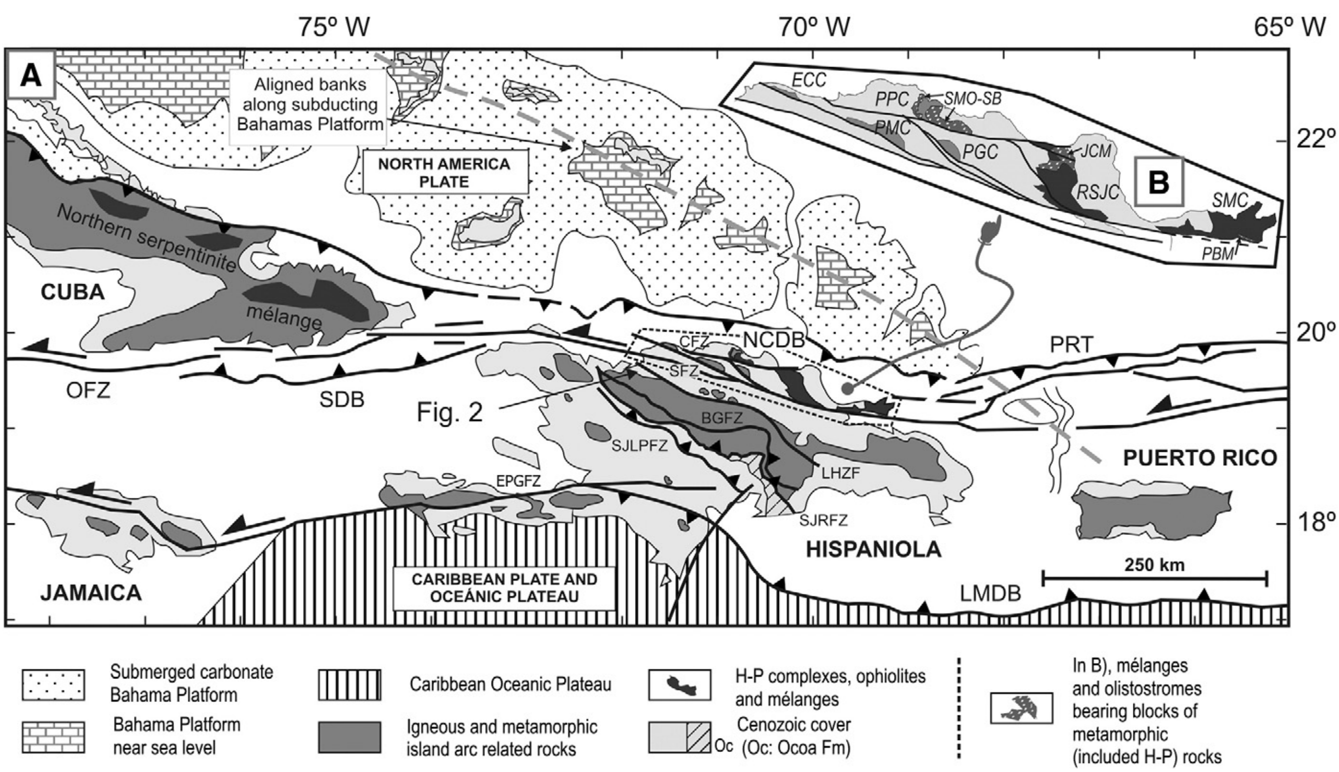

Fig. 1. (A) Map of northeastern Caribbean plate margin, outlying major tectonic features, modified from Dolan et al. (1998). Inset box shows the location of Cordillera Septentrional and Península de Samaná, enlarged in Fig. 2. Approximate outcrop of Ocoa Fm within Cenozoic cover is indicated with inclined bars. OFZ, means Oriente fault zone; SDB, Santiago deformed belt; NCDB, Northern Caribbean deformed belt; PRT, Puerto Rico trench; LMDB, Los Muertos deformed belt; CFZ, Camú fault zone; SFZ, Septentrional fault zone; LHFZ, La Hispaniola fault zone; BGFZ, Bonao-La Guácara fault zone; SJRFZ, San José-Restauración fault zone; SJLPFZ, San Juan Los Pozos fault zone; EPGFZ, Enriquillo Plantain Garden fault zone (B) Simplified structural sketch of Dominican Cordillera Septentrional with the location of basement complexes and mélanges and olistostromic units. EEC means El Cacheal complex; PMC, Palma Picada complex; PGC, Pedro García complex; PPC, Puerto Plata complex; RSJC, Río San Juan complex, SMC, Samaná complex; JCM, Jagua Clara mélange; SMO-SB: San Marcos olistostrome-Serpentinite Breccias unit; PBM, Punta Balandra unit (+mélange).

In the Río San Juan basement complex (RSJC) of eastern Cordillera Septentrional, the outcrop comprised of high-P metamorphic rocks in the form of blocks associated with serpentinite mélanges (e.g. Jagua Clara mélange) has been traditionally linked to the subduction processes between the Caribbean and North American plates (Draper and Nagle, 1991; Nagle, 1974, 1979) and have more recently been interpreted to mark the position of the exhumed subduction channel (Krebs et al., 2008). Like Samaná, Río San Juan is a subduction related metamorphic complex whose internal structure consists of an imbricate stack of slabs bearing high-P rocks. In this case, most of the compounding units outcropping south of the Jagua Clara mélange belong to the accreted or subducted volcano-plutonic part of the island arc assemblage. From north to south, these units are (Fig. 2) El Morrito unit, which comprises the (green to blueschist facies) metavulcanites and quartz-feldspathic Puerca Gorda and El Guineal Schists subunits that are identified with volcanic rocks of the island arc crust; the Río Boba batholith, composed of variably metamorphosed (amphibolite to granulite facies) gabbros, gabbro-norites, diorites and tonalites, that correspond to the plutonic/metaplutonic island arc complex; and, La Cuaba unit, formed by amphibolites and orthogneisses (and associated metacumulates and peridotites) also interpreted as fragments of the island arc crust that have been transformed by subduction processes to amphibolite and eclogite (and locally even to ultra high-P facies with coesite) facies. The Jagua Clara mélange occupies the northern part of the complex, where it appears interleaved with slices of peridotites and occasional mafic (Hicotea) schists. According to lithological similarities, their respective structural positions and comparable ages (obtained and deduced) of return flow exhumation in a subduction channel, Escuder-Viruete et al. (2011) have suggested the correlation between the Jagua Clara and Punta Balandra mélanges. This correlation has led these authors to propose that the RSJC structurally overlies the Samaná complex as a consequence of an accreting process that starts with the beginning of exhumation (and subsequent exposure at surface) of the Jagua Clara mélange between 73 and 62 Ma and progresses toward the foreland during the Paleogene, up to the exhumation of the last, structurally lower and northernmost slabs of the Samaná complex (El Rincón and Playa Colorada nappes) in Early Miocene.

High-P rocks have also been found to be included in different kinds of chaotic formations spatially related to the Puerto Plata basement complex (PPBC) in the Puerto Plata area, thus enabling a general correlation with the Río San Juan complex and, to some extent, rendering valid the same subduction-related interpretation proposed (Bowin and Nagle, 1982; Eberle et al., 1982; Nagle, 1979; Pindell, 1985; Pindell and Draper, 1991). However, the associated chaotic formations that host high-P exotic (non *in-situ* outcropping) blocks and other non exotic (mostly derived from the PPBC) blocks show a sedimentary provenance: the San Marcos Fm on one side, which was originally defined as an olistostrome (Nagle, 1966, 1979) and another formation that is predominantly made up of fragments and blocks of serpentinized peridotites embedded in an abundant matrix of the same composition. The latter has been recently mapped (together with previously recognized serpentinite breccias) in a separate and more extensive unit unconformably overlying the outer limits of the PPBC at the base of the San Marcos Fm. Both formations (San Marcos and Serpentinite Breccias), contain (relatively) abundant metamorphic exotic blocks (including high-P rocks) that appear spatially related to the Camú fault trace, one of the major regional scale, long-lived, strike slip faults in the Cordillera Septentrional, leading to suggest that fault-controlled mud diapirism was the mechanism responsible for their emplacement (Pindell, 1985; Pindell and Draper, 1991).

This paper gathers new data acquired during a 1:50.000 geological mapping campaign carried out in the Puerto Plata area as part of a larger mapping project of the Cordillera Septentrional within the context of the Dominican Republic Geothematic Mapping Project funded by the EU (European Union) SYSMIN Program. Beyond a geological review of this area, the paper focuses on the cartographic expression (including aeromagnetic data), stratigraphic position and ages of the 'mélange-type' units, San Marcos and Serpentinite Breccias Fms., and describes their relationships with the PPBC and the Imbert Formation, the latter being traditionally interpreted as the sedimentary cover overlying this complex. The discussion addresses the significance of

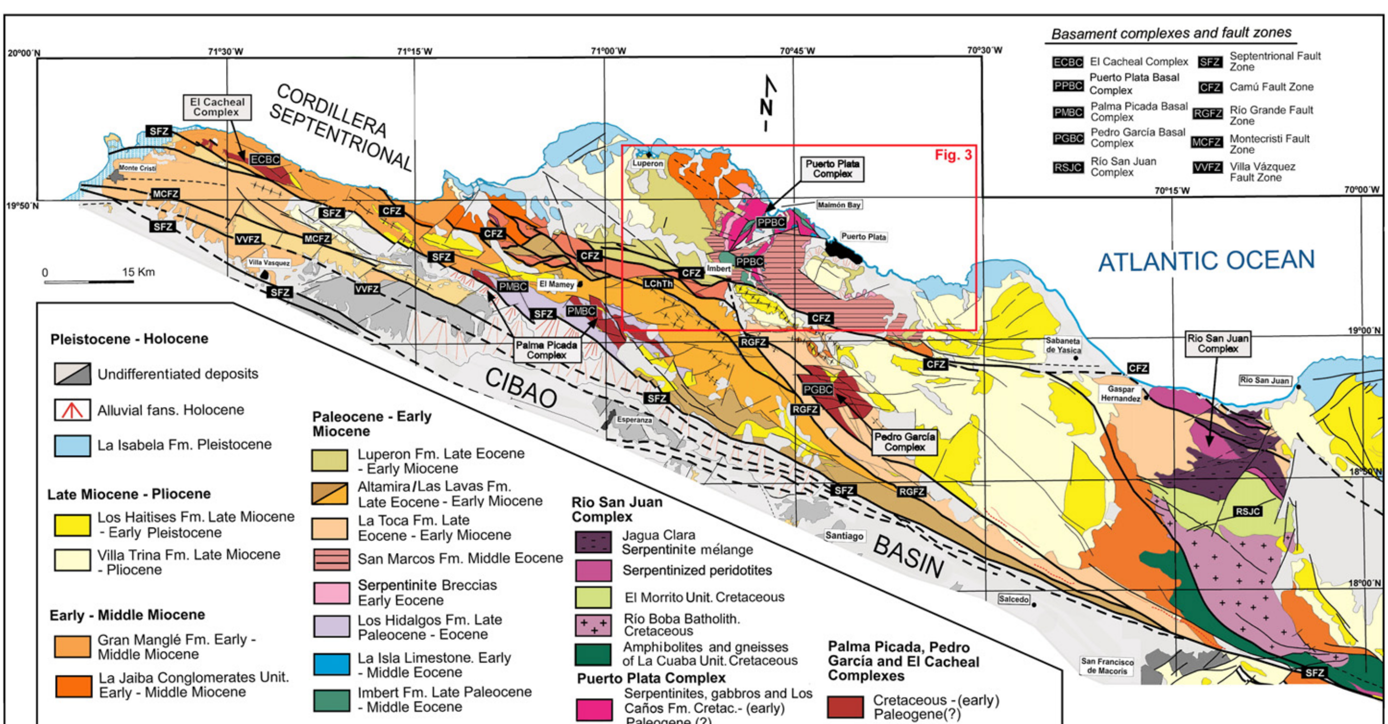

Fig. 2. Simplified geological map of the Dominican Cordillera Septentrional adapted after the compilation of the SYSMIN Geothematic Mapping Project. See regional location in Fig. 1. The inset box shows the location of the study area enlarged in Fig. 3A.

these units and their mode of emplacement within an end of subduction context and the subsequent collisional processes between the Caribbean and North American plate in the Cordillera Septentrional. Furthermore, it aims to provide a tentative paleotectonic scenario of the Puerto Plata area during Eocene times by comparison with the Río San Juan (accretionary) complex.

2. Geological setting

The island of Hispaniola is located on the northern margin of the Caribbean plate (Fig. 1.), and consists of a tectonic collage of fault-bounded igneous, metamorphic and sedimentary basement rocks of Late Jurassic to Early Paleogene age, accreted in an intra-oceanic island-arc setting. These rocks are overlain by a cover of Late Eocene to recent siliciclastic and carbonate sediments that post-date the island arc activity and record the period of dominant left-lateral strike-slip motion between the North American and Caribbean plates after the Eocene collisional event (cf., Bowin, 1975; Draper et al., 1994; Mann et al., 1991; Pérez-Estaún et al., 2007, for regional reviews).

The Cordillera Septentrional is a 15 to 40 km wide WNW-ESE oriented mountain range that runs parallel to the northern coast of the Dominican Republic (Figs. 1 and 2). It is made up of volcano-plutonic and metamorphic complexes of Cretaceous to early Paleogene age that in turn make up the basement of large, late Paleogene and Neogene sedimentary basins resting unconformably on the former (Fig. 2). Neogene to present transpressive deformation is partitioned into several main strike-slip faults or fault zones (Septentrional, Camú, Río Grande, among others) and coeval related folding that result in an important tectonic-controlled relief. The basement complexes outcrop in a NW-SE direction, slightly oblique to the dominant WNW-ESE structural fabric of the Cordillera and arranged in a right-stepping *en echelon* pattern, associated with kilometric-scale restraining bends and consistent with regional left lateral shearing. (Fig. 2).

Several basement complexes are predominantly made up of high-P metamorphic rocks (or they incorporate these rocks into mélanges and olistostromic formations) with subordinate plutonic and volcanic rocks, located to the north of the Camú (Puerto Plata basement complex) and Septentrional faults (Río San Juan basement complex), while other complexes consist of igneous, volcanic and plutonic rocks, mostly deriving from volcano-sedimentary island arc magmatic processes, without metamorphism nor presence of high-P rocks, located between the Camú and Septentrional faults (El Cacheal, Palma Picada and Pedro García complexes), (Calais et al., 1992; de Zoeten and Mann, 1991; Eberle et al., 1982; Muff and Hernández, 1986) (Figs. 1 and 2). The former have been traditionally interpreted to overlie a subducting slab in the prism area and the latter are thought to underlie the forearc basin. These northern and southern terrains appear nowadays juxtaposed by means of the aforementioned major faults or fault zones whose relative displacement remains unquantified.

The Puerto Plata basement complex (PPBC) consists of highly faulted and dismembered blocks formed by discontinuous but sometimes coherent outcrops of serpentinized or massive peridotite, massive or banded gabbroid cumulates (with pods of pyroxenites) and Los Caños Fm, which is a thick sequence of grossly bedded volcanoclastic material with interbedded basaltic (sometimes pillowed) or andesitic flows (Nagle, 1979) (Fig. 3A and B). Based on these rock associations and the relationship with nearby mélange-type formations, the PPBC has been traditionally identified as an ophiolitic fragment accreted from the subducting (North-American) slab (e.g. Bowin and Nagle, 1982; Eberle et al., 1982; Pindell, 1985; Pindell and Draper, 1991; Saumur et al., 2010). In addition, recent mapping has also revealed a hectometre-scale body of leucogranites intruding into Los Caños Fm. These rocks bear very low-grade (or no) metamorphism and lack a general deformation fabric, apart from displaying occasional transformation to mylonites along major contacts due to localized shearing. New geochemical analyses of gabbros, volcanic rocks from Los Caños Fm and leucogranite samples performed in the context of the mapping project revealed an island arc signature (IAT, *island arc tholeiites*) similar to the one obtained in the volcano-plutonic island arc complexes located in the southern side of the Camú fault and comparable to other well characterized island arc rocks of La Hispaniola (e.g. Los Ranchos Fm; Escuder-Viruete et al., 2006, 2007; Escuder-Viruete, 2010; unpublished data). However, these analyses are insufficient to discriminate whether PPBC rocks were formed exclusively during an Early Cretaceous primitive island arc (PIA) stage or they (most probably) also record the subsequent Late Cretaceous (−early Paleogene?) calc-alkaline island arc magmatic event.

The age of the PPBC complex is poorly constrained. The only reported (micro)-paleontological dating information includes a couple of separate and imprecise references to Early Cretaceous foraminifera and radiolaria content found in the inter-pillow material of pillow lavas that supposedly belong to the PPBC (Draper and Pindell, 2008), one of them being in fact a block included in the San Marcos Fm (Bourgois et al., 1982; Pindell and Draper, 1991). On the other hand, new geochronological dating performed in the PPBC within the context of the SYSMIN project shows a wide range of radiometric ages that do not allow a straightforward interpretation. A detailed analysis and interpretation of these results is out of the scope of this study and will be subject to revision when presented and discussed elsewhere. Nevertheless, these results are shown in Table 1 and are briefly summarized as follows, in chronological order. One sample of gabbros and gabronorites has yielded the oldest (U/Pb on zircons) age of 126 ± 0.3 Ma, consistent with the Early Cretaceous development of PIA magmatism. One sample of leucogranites that clearly intrude rocks of los Caños Fm has yielded an ($^{40}Ar/^{39}Ar$ on biotite) age of 95.4 ± 1.2 Ma and may constrain the age of (part of) this formation to pre-Turonian/Cenomanian times. However, one sample of andesite from Los Caños Fm has yielded an ($^{40}Ar/^{39}Ar$ on hornblende) age of 81.60 ± 2.70 Ma which instead suggests a clear Late Cretaceous (Campanian) emplacement or cooling age of at least a part of it. Another sample collected in the PPBC gabbroic unit consisting of banded troctolites has yielded an ($^{40}Ar/^{39}Ar$ on hornblende) age of 55 ± 8.0 Ma, which closely matches the consistent and uniform ages obtained from volcanic and plutonic rock samples of the Palma Picada and Pedro García complexes (Table 1), suggesting altogether that the average timing of the latter two correspond to late stage island arc magmatism. The youngest ($^{40}Ar/^{39}Ar$ on plagioclase) age in the PPBC of 35.8 ± 8.1 Ma has been obtained again from another sample of banded gabronorites, indicating that relict magmatism might eventually extend until Late Eocene or, most probably, may record the timing of uplift and cooling of the complex. It is worth noting that in spite of the significant differences in ages obtained from samples collected throughout the gabbroic unit of the PPBC, no evidence of separate bodies or stocks displaying cross-cutting relationships that may account for such a varied range of absolute dates has been observed in the field, although these should not be discarded.

The PPBC has a NE-SW orientation that is notably transversal to the regional WNW-ESE trend of the Cordillera, imposed both by the general attitude of the (rarely observed) bedding in Los Caños Fm and, mainly, by the direction of internal faulting. Due to the lack of observable contacts between faulted blocks, the internal structure of the complex is difficult to decipher. According to their mapping patterns, these contacts are shown as subvertical normal faults in cross sections I-I′ and II-II′ of Fig. 3(B), and thus (generally) agree with Pindell and Draper (1991) who propose that the complex can be structurally interpreted as an ‘extensional inlier’. Following these authors' interpretation, normal faulting may be explained as a local structural feature (eventually superimposed to main compressional

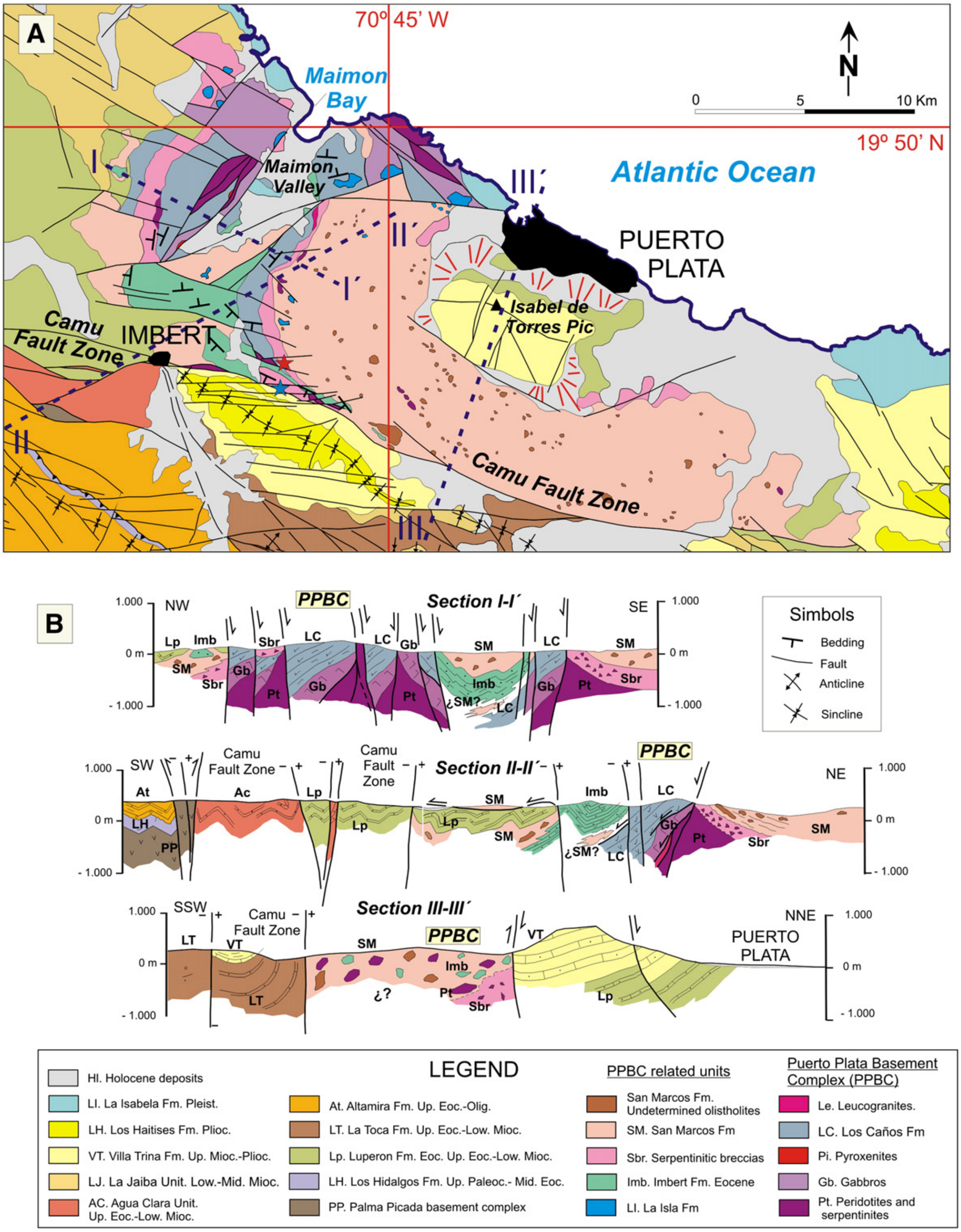

Fig. 3. (A) Simplified geological map and (B) geological cross-sections of the Puerto Plata area, adapted from the compilation of SYSMIN 1:50.000 geologic maps of Puerto Plata-6075-I (Monthel, 2010a; unpublished results), Imbert-6075-III (Hernaiz Huerta, 2010; unpublished results) and Luperón-6075-IV (Monthel, 2010b; unpublished results). The red and blue stars show the approximate location of the Río Obispo and the Arroyo Corozal sections respectively, referred to in the text. In sections, symbol (+) indicates that the block moves inwards, and symbol (−) that the block moves outwards. The legend applies to both map and the cross sections.

or transpressional – thrusts and folds – deformation) consistently attained by the PPBC during the early stages of left lateral strike-slip wrenching, which might have facilitated or enhanced the uplift and subsurface exposure of serpentinite and related PPBC lithologies. Most of these normal faults show further reactivation as strike-slip faults and some of them have morphological expression, especially along the western margin of the Maimón valley, located south of Maimón Bay (Fig. 3A). To summarize, the above compilation of data suggests that the PPBC seems to represent a tectonically accreted and uplifted fragment of the island arc or forearc assemblage rather

Table 1
Summary of geochronological results obtained in rock samples of island arc basement complexes of Western Cordillera Septentrional collected in the context of the Dominican Republic Sysmin Geothematic Mapping Project. Datings have been performed in the Pacific Center of Isotopic and Geochemical Research (PCIGR), Department of Earth and Ocean Sciences of British Columbia University. See text for explanation.

Sample	Geograph. coordinates		Complex/unit or formation	Lithology	Age (MA)	Method
	Lat. (N)	Long.(W)				
6075IV-JE9119B	19,8364	70,7593	Puerto Plata BC / Gabbros and gabbronorites	Banded gabbro and gabbronorite	126.1 ± 0.3	$^{206}Pb/^{238}U$ on zircons; minimum age (only one concordant fraction)
6075III-HH9124	19,8121	70,8061	Puerto Plata BC / Gabbros and gabbronorites	Banded troctolite	55.0 ± 8.0	$^{40}Ar/^{39}Ar$ on Hbl; plateau
6075II-JM9112	19,8254	70,7435	Puerto Plata B / Gabbros and gabbronorites	Banded gabbronorite	35.8 ± 8.1	$^{40}Ar/^{39}Ar$ on Plg; plateau
6075II-JM9271	19,8352	70,7719	Puerto Plata BC / Los Caños Fm	Porphyritic andesite	81.60 ± 2.70	$^{40}Ar/^{39}Ar$ on Hbl; plateau
6075II-JM9272B	19,8365	70,7715	Puerto Plata BC / Los Caños Fm	Porphyritic andesite	81.90 ± 5.80 / 91 ± 11.00	$^{40}Ar/^{39}Ar$ on Hbl; non plateau, normal and inverse isocrons
6075III-HH9133	19,8024	70,7755	Puerto Plata BC / Intrusion in Los Caños Fm)	Leucogranite	95.4 ± 1.2	$^{40}Ar/^{39}Ar$ on Bio; plateau
5975III-PU9697	19,8223	71,3151	El Cacheal BC	Riolite	122.7 ± 0.30	$^{206}Pb/^{238}U$ on xenocristals
					90.90 ± 0.50	$^{238}U/^{206}Pb$ on zircons
5975II-FP9091	19,7489	71,1616	Palma Picada BC	Spilitized brecciated basalt	64.26 ± 0.96	$^{40}Ar/^{39}Ar$ WR; plateau
6075III-HH9126	19,7069	70,9750	Palma Picada BC	Porphyritic basalt	50.44 ± 0.85	$^{40}Ar/^{39}Ar$ on Hbl; plateau
6075III-HH9128	19,6915	70,9747	Palma Picada BC	Porphyritic basalt	49.7 ± 0.5	$^{40}Ar/^{39}Ar$ on Hbl; plateau
6074I-JR9073	19,6239	70,6907	Pedro García BC	Gabbro/Diorite	49.8 ± 2.90	$^{40}Ar/^{39}Ar$ on Hbl; plateau
6074I-JR9229C	19,6247	70,6908	Pedro García BC	Tonalite	47.26 ± 0.59	$^{40}Ar/^{39}Ar$ on Hbl; plateau
6074I-JR9071	19,6221	70,6909	Pedro García BC	Andesite	46.30 ± 2.40	$^{40}Ar/^{39}Ar$ on Hbl; plateau

than, as traditionally proposed, an ophiolitic piece peeled off the subducting slab or incorporated from it as a large block or a broken formation that was part of a mélange.

The Imbert Fm is a unit of capital importance as it is the oldest sedimentary formation recognized as such in the area. Dating of planktonic foraminifera in the formation suggests that it is Eocene (or Paleocene?-Eocene) in age (Nagle, 1979; Pindell and Draper, 1991). The formation consists of a well-bedded succession of volcanogenic sandstones and tuffites (frequently white, very fine grained porcellanic tuffites), with intervals of breccias and debris. These last ones typically incorporate fragments of serpentinized peridotites and blocks of volcanic rocks identified in the PPBC, as well as some occasional blocks of metamorphic (exotic) rocks. The Imbert Fm is also internally disrupted and although not a single clear contact can be observed in the field, it is considered to rest unconformably over the PPBC, thus post-dating exhumation of the latter (Fig. 4). An Imbert Fm has also been described in the Río San Juan complex (RSJC), unconformably overlying metamorphic rocks and the Jagua Clara serpentinite mélange (Draper and Nagle, 1991).

Apart from the mélange-type formations that are described separately in the next section, La Isla Limestone (Nagle, 1979) represents another controversial unit that relates to the PPBC. As deduced from mapping patterns and despite the absence of contacts observed in the field, La Isla Limestone apparently rests unconformably on the Serpentinic Breccias and the different units of the PPBC (Fig. 3A), and can be also found as blocks, olistoliths or even centimeter-size fragments included in both the Serpentinite Breccias unit and the San Marcos Fm. Therefore, the stratigraphic position of this unit has been a matter of discussion, as it is considered that the shallow (reefal) facies of the limestones might reflect the near-surface (submarine) exhumation of the basement complex, while its age (so far undetermined) could provide clues for dating this particular event (Nagle, 1979; Pindell and Draper, 1991).

The Luperón Fm (Nagle, 1979) uncomformably overlies the PPBC and aforementioned related units (Figs. 3A and B, 4), although contacts have never been identified at outcrop scale. This unit is made up of a sequence of orange colored, indurated micaceous sandstones alternating with marls and clayly lutites in addition to more occasional intervals of calcareous bioclastic sandstones and conglomerates (Nagle, 1966, 1979). In the lowermost part of the section, the conglomerates bear clasts and blocks belonging to PPBC units and the Imbert Formation. The age of the Luperón Formation was previously determined to range from Late Eocene to Late Oligocene (Bourgois et al., 1983; Nagle, 1966, 1979) although recently the top of the section below the unconformable La Jaiba Fm (Figs. 3A, 4) has been dated as Early Miocene (Burdigalian; SYSMIN Project, unpublished data), and is therefore coeval to the Altamira and La Toca Fms (Fig. 3A) which in turn overly the island arc basement complexes located in the southern side of the Camú fault (de Zoeten and Mann, 1991). Above the Luperón Fm and any other preceding unit, the Late Miocene–Pliocene/Pleistocene marine marls and bioclastic sandstones of the Villa Trina and Los Haitises Fms (de Zoeten and Mann, 1991) represent the youngest, regional scale sedimentary cycle of the Cordillera Septentrional, showing a general unconformable contact with all of the underlying rocks (Figs. 3A and B, 4).

3. Mélanges and olistostromes in the Puerto Plata area: the Serpentinite Breccias unit and the San Marcos Fm

3.1. The Serpentinite Breccias unit

Nagle (1966, 1979) described the way in which his massive and brecciated serpentinite units occur, and called the attention on the sedimentary appearance of some of the latter. Both types of units were eventually included in the PPBC. Pindell and Draper (1991) confirmed the sedimentary origin of the serpentinite breccias

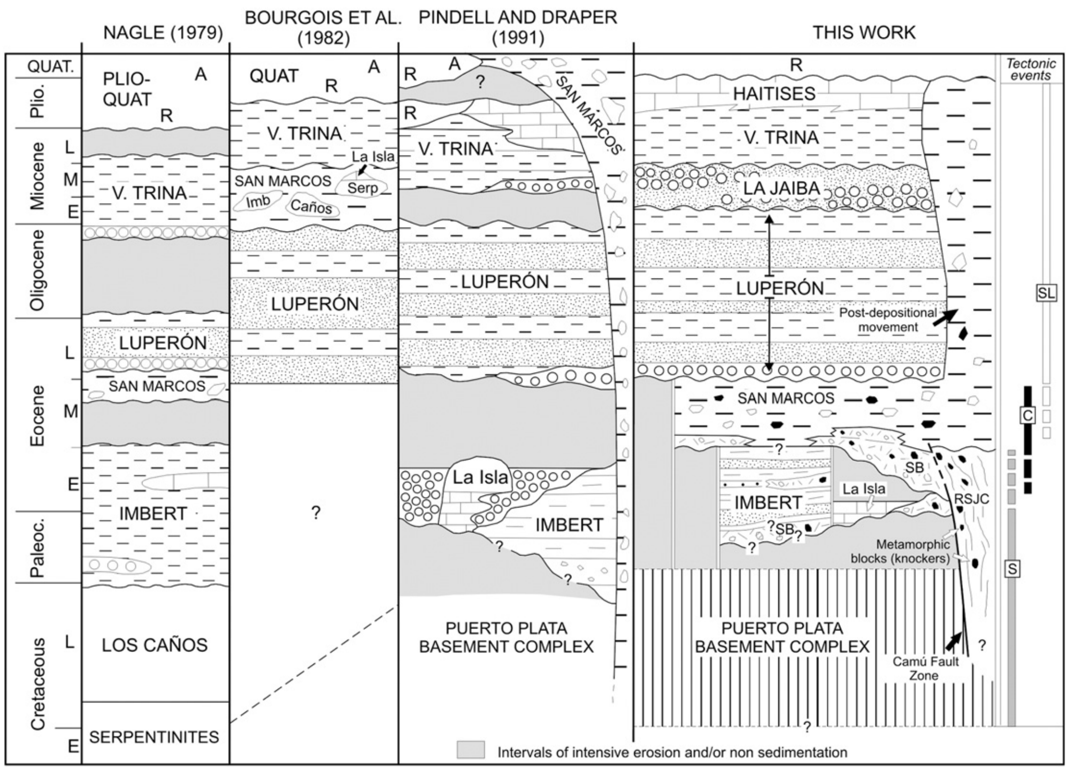

Fig. 4. Stratigraphic section (and related major tectonic events) of the Puerto Plata area proposed in this work and comparison with others presented in previous works (modified from Pindell and Draper, 1991). A: Alluvium; R: Reefs; SB: Serpentinite Breccias unit; RSJC: Río San Juan complex; S: Subduction; C: Collision; SL: Strike slip.

associated with the outcrops of La Isla Limestone to the west of Maimon Bay and included both lithologies under La Isla Fm. Additionally, these authors defined the *Barrabas mélange* as a unit formed by blocks of metamorphic rocks (among others) embedded in a matrix of serpentinite breccias that outcrops in the upper reaches of the Río Obispo, near the village of Barrabas. The authors however did not specify the relationships with nearby units.

New investigations conducted in the study area recognize for the first time a separate mappable unit of Serpentinite Breccias distributed mainly along the outer limits of the PPBC, but also in several scattered outcrops within (Fig. 3A and B). The unit is dominantly made up of fragments and blocks of serpentinized peridotites, embedded in a mostly pebble-size, only locally schistose (serpentinized) and proportionally variable (25–75%) matrix of the same composition that includes subordinate blocks from probable PPBC units (gabbros and Los Caños basalts) and Imbert and La Isla Fms, as well as other (minor) exotic blocks of unknown origin (Figs. 5 and 6). In the southeastern limit of the complex near the Camú fault, there is a particularly high concentration of exotic blocks deriving from metamorphic rocks (greenschists, amphibolites, marbles and even blueschists) that are not exposed in any other neighboring areas, thus suggesting deep-sited, subduction-related, sources (Pindell, 1985; Pindell and Draper, 1991). The basal contact of this unit with the rocks of the PPBC is usually faulted and difficult to observe in the field, but cartographic patterns suggest that it represents an unconformity (Figs. 3A and B, 4).

Metamorphic blocks present in the Serpentinite Breccias unit can be considered as exotic blocks or knockers (Karig, 1980), as none of these blocks has a recognizable source area at the surface. A list of the main types of blocks identified in this unit is shown in Fig. 5. Detailed petrographic descriptions of these blocks are out of the scope of this work and can be found in (Escuder-Viruete, 2010). An actinolitic mafic greenschist block of hectometre size has been mapped in the Arroyo Corozal section (Fig. 3A) and it is possible that it is the same block identified by Pindell and Draper (1991) as *Hicotea schist*, by correlation with the so named unit outcropping in the Río San Juan complex, which is structurally interleaved with the Jagua Clara serpentinite mélange. In the Arroyo Corozal section, the lithological nature of the blocks is quite varied (e.g. serpentinites, diverse metamorphic blocks, volcanic rocks, Imbert Fm) and the general appearance of the unit is half way or a mixture between the Serpentinite Breccias and the San Marcos Fm (Figs. 5 and 6E and F).

Outcrops of serpentinite breccias show general internal chaotic organization with a wide variety of block-in-matrix fabrics and block content, but most of them also show pieces of evidence of sedimentary high density sub-aqueous mass transport rework. In spite of the essentially chaotic pattern, in many scattered points (specially those with finer grained intervals) it is possible to recognize an unquestionable sedimentary internal arrangement with channel-like erosive bases and positive grading (Fig. 6E and F).

The tectonic (and diapiric) emplacement of serpentinite-rich chaotic or mélange type units has been widely characterized in subduction contexts (Federico et al., 2007; Guillot et al., 2000; Hattori and Guillot, 2007; Page et al., 1998) and strike-slip related settings (Harlow et al., 2004; Jouanne et al., 2010; Moore and Rymer, 2007; Weissert and Bernoulli, 1985) around the world. However, the involvement of sedimentary processes in formation, emplacement, and deposition of these serpentinite units has been relatively less documented and is controversial. Lockwood (1971) first brought the attention to the worldwide existence of sedimentary serpentinites, suggesting gravity-slide processes for their emplacement; he specifically mentioned the sedimentary character of some serpentinite units found in the California Coastal Ranges, so coinciding with previous descriptions of Moiseyev (1970). Carlson (1984) noticed the content of metamorphic blocks in these serpentinite units, located within the basal part of the Great Valley Group (GVG) forearc basin deposits that structurally overly the Franciscan subduction complex. Phipps (1984) and Fryer et al. (2000) provided a subsequent revision of these serpentinite deposits. Wakabayashi (2012-this volume) describes multiple Franciscan serpentinite mélange localities in detail

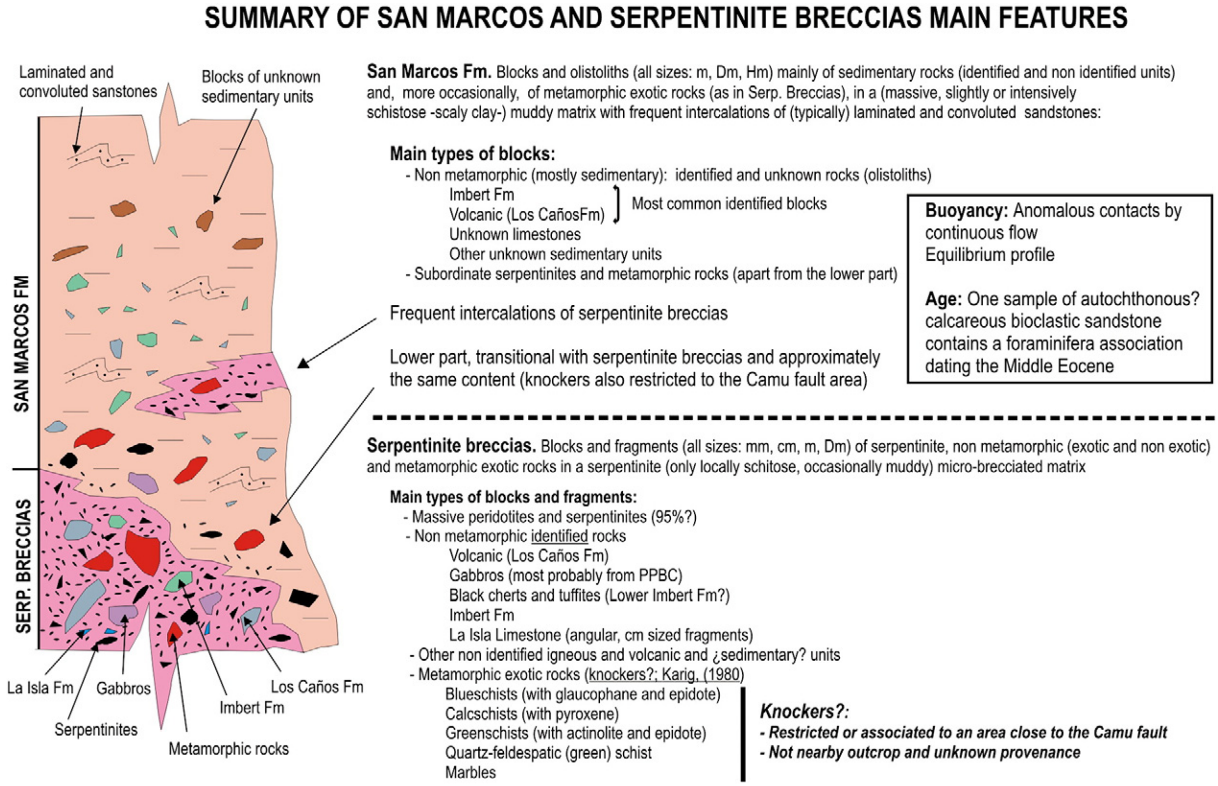

Fig. 5. Cartoon summarizing the basic relationships, main lithologic features and block content, of the Serpentinite Breccias unit and San Marcos Fm.

and discusses the pieces of evidence of their sedimentary origin. With regard to serpentinites found in northern Dominican Republic, recent studies carried out by Saumur et al. (2010) discard any kind of sedimentary rework potentially responsible for the emplacement. On the other hand, serpertinitic breccias can be produced either by sedimentary or tectonic processes, although in the absence of companion sedimentary deposits, discerning between the two possible alternatives is rendered difficult, more so if an intense, subsequent episode of deformation overprints the original depositional features. Comas et al. (1996) have approached the origin of serpertinized peridotitic breccias in a transform fault context, concluding that the serpentinite breccias produced by cataclastic faulting feed nearby olistostromic deposits, together with other volcanic and sedimentary units.

In this work, it is believed that the most common, previously described features of the Serpentinite Breccias have clear sedimentary patterns and thus it can be interpreted that a significant amount of this unit is formed by the sedimentary rework of peridotitic bodies tectonically emplaced in the PPBC. On the other hand, the reworking of subduction channel and other accreted metamorphic rocks from RSJC constitutes the other most probable feeding mechanism for the supply of serpentinized peridotites, and of high-P exotic blocks, to the basin. No direct dating of the Serpentinite Breccias unit is available. Nevertheless, according to cartographic patterns, stratigraphic position and mixture relationships with respect to the San Marcos Fm, the age of the unit is estimated to be similar to or slightly older than this formation (i.e. Late? Eocene).

3.2. The San Marcos Fm

The serpentinite breccias make up the base of the San Marcos Fm (Figs. 2, 3A and B, 4, 5) in the easternmost part of the PPBC, which corresponds to another chaotic or mélange-type unit widely represented in the region. Nagle (1966, 1979) formally defined this formation by describing its essentially disorganized appearance and particular content (made up of various kinds of blocks) and eventually interpreted it as an olistostrome. Nagle (op. cit.) made other interesting observations in this unit. Based on the general, inaccurate foraminifera associations found, he proposed a rough Paleocene–Eocene age range within which he identified a probable Middle to Late Eocene target age (Fig. 4), as inferred from the presence of blocks of the Imbert Fm. From the results of X ray analyses he suggested that the clays forming the olistostrome matrix possibly originated from the reworking of the Imbert Fm tuffites; and inferred intuitively that the emplacement of the unit took place in water saturated conditions, thus enhancing internal deformation. In later works (Bourgois et al., 1982, 1983; Bowin and Nagle, 1982; Eberle et al., 1982; Pindell, 1985; Pindell and Draper, 1991), the discussion has focused on the age, stratigraphic position (Fig. 4), way of emplacement and the regional or geodynamic significance of this formation. The age of the San Marcos Formation is disputed owing to the lack of reliable dates and the controversial stratigraphic relationships with neighboring units (see summary in Pindell and Draper, 1991 and discussion therein). The foraminifera associations obtained from a sample of (autochthonous) bioclastic marly sandstones found interbedded within the San Marcos Fm as part of the new mapping project has yielded a reliable Middle Eocene age (Fig. 4).

The San Marcos Fm outcrops exclusively in the northern side of the Camú fault zone, displaying cartographic patterns similar to those of the Serpentinite Breccias unit (i.e. within the PPBC and surrounding it) mainly toward the eastern border where it mixes with and rests on the breccias, while occupying a large extension (> 125 km^2) between the towns of Imbert and Puerto Plata with a rough synformal structure and unconformably overlain by the Villa Trina Fm of Pico Isabel de Torres (Fig. 3A and B). It is worth highlighting that the image of the Thorium anomaly obtained in airborne geophysical surveys (Fig. 7) shows a nearly perfect match with the map pattern of San Marcos Fm.

At outcrop scale, the San Marcos clays are gray to bluish, sometimes brown to darkly tanned, colored lutites or marly lutites in fresh sections (whitish when altered) that typically present variably pervasive satin fabric or *scaly clay* or *argile scagliosa* type cleavage. This cleavage can be somewhat pervasive to very conspicuous, but the formation overall

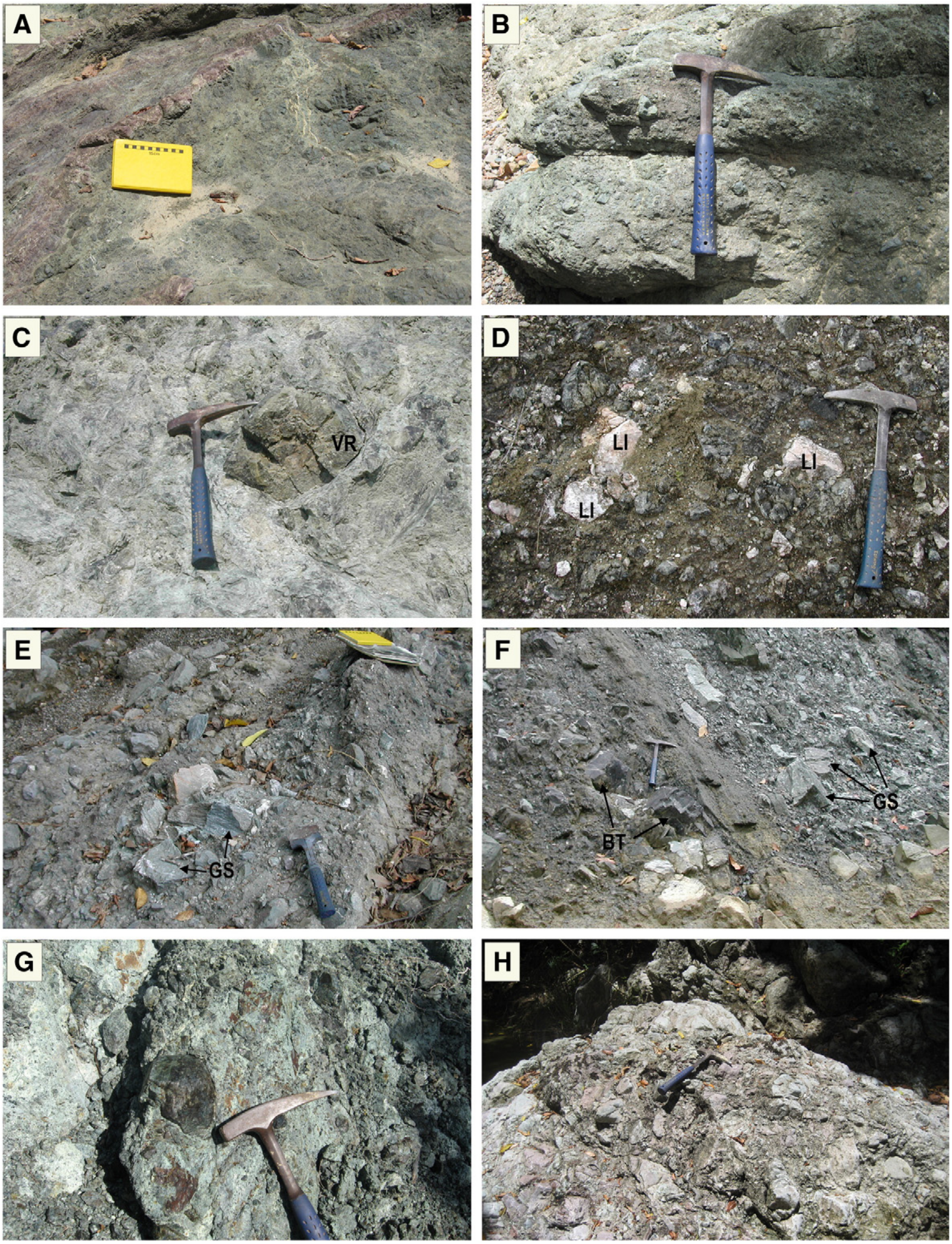

Fig. 6. Photographs of different outcrops of the Serpentinite Breccias unit in the Puerto Plata area: (A and B) Gravel-sized serpentinite breccias made entirely of serpentinite fragments in a relatively scarce matrix of the same composition showing gross sedimentary rework; Río Obispo section at Barrabas village (C) Serpentinite breccias made of cobble-sized fragments of serpentinized peridotite and minor volcanic (basalt-andesite?) rocks (VR) within a relatively abundant gravel-sized and partially schistose serpentinite matrix; west of Maimon Bay; (D) Subangular gravel and cobble-sized (light colored) fragments of La Isla Limestone (LI) included in the Serpentinite Breccias unit; west of Maimon Bay, very near (<50 m) the outcrop shown in the previous photograph; all other fragments shown in the photograph are made of serpentinized peridotite, (E) Gross-bedded serpentinite breccias full of blocks of metamorphic (mostly mafic greenschists — GS -) rocks; Río Obispo section (f) Similar facies to the ones shown in the previous photograph, in this case in Arroyo Corozal section, showing a well bedded (and upward-thinning) interval; most lighter colored blocks to the right hand side (above) of this interval are mafic greenschists (GS), and many of the darker colored blocks to the left hand side (below) of it are black siltstones and tuffites (BT) probably eroded from the (Lower) Imbert Fm; many other blocks of unknown origin are recognized in both this single and nearby outcrops; facies shown in (E) and (F) outcrop near the San Marcos Fm and show a certain level of mixture with this formation; (G) Massive serpentinite breccias made of cobble and gravel sized fragments of serpentinized peridotites within a relatively abundant matrix of serpentinites, near La Colorada village; (H) Debris of blocks of unknown calcareous mudstones and tuffites (Imbert Fm?) included in a major outcrop of serpentinite breccias.

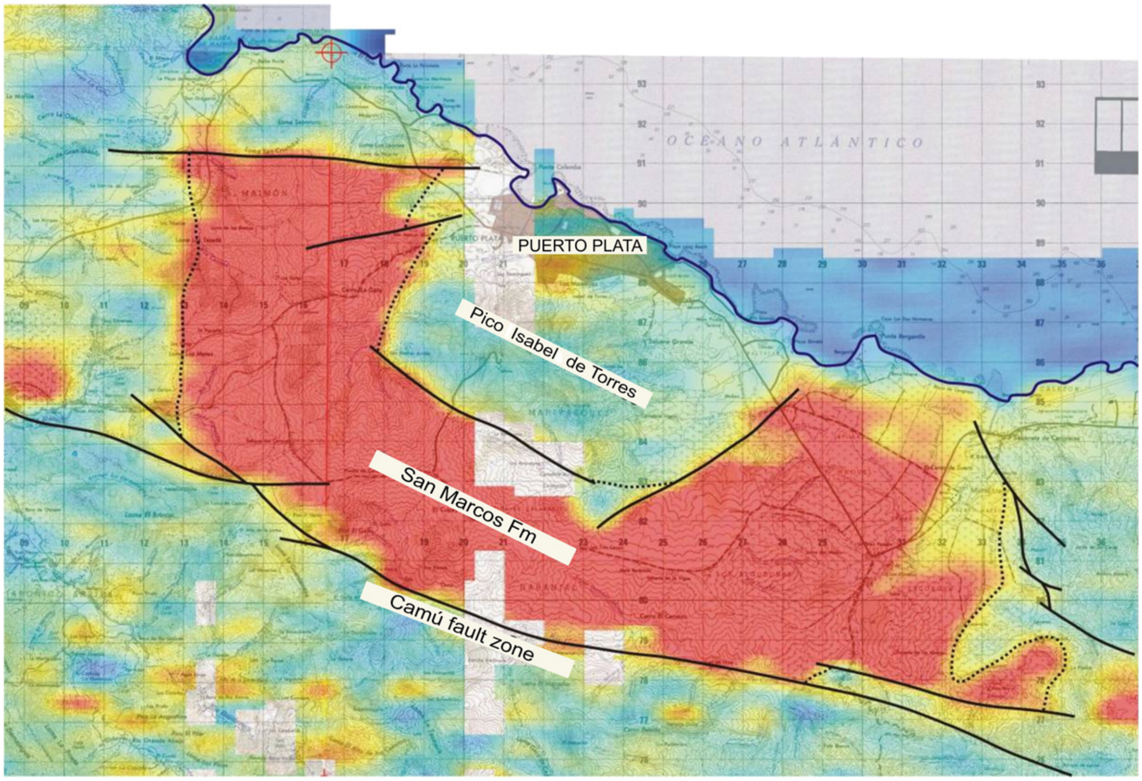

Fig. 7. Thorium image obtained from airborne geophysical survey of the area around Puerto Plata. Compare with the geologic map in Fig. 3 to observe the good fit of this anomaly with the mapped distribution of San Marcos Fm. Some differences in the mapping pattern of the Camú fault are irrelevant for the purpose of this figure.

is rarely massive (Fig. 8A and B). The lutites include centimeter to decimetre-thick autochthonous beds of convoluted turbidite sandstones (Fig. 8D) that appear discontinuous, dismembered and folded due to flow processes, together with the argillaceous matrix, causing the whole complex to display an absolute lack of internal coherence. The formation incorporates frequent intercalations or different size bodies of serpentinite breccias at all levels but specially in the structurally lower parts (Fig. 8C and F). These are the same kind of breccias as the ones present in the underlying unit described in the previous section. The new mapping shows that the San Marcos Fm is largely substituted by the aforementioned Serpentinite Breccias unit immediately above the contact with the PPBC, and it is suspected that the contact between the two may be transitional or correspond to a zone of mixture as seen in several outcrops near the town of Imbert. South of the town of Puerto Plata several thick intervals of serpentinite breccias have been mapped in the upper part of the section, near the upper contact with the Miocene marine marls of Villa Trina Fm outcropping in Pico Isabel de Torres (Figs. 3, 8C).

The olistostrome includes exotic blocks similar to those observed in the serpentinite breccias and blocks and olistoliths that derive from the PPBC but mainly from the Imbert Fm and other undetermined sedimentary units (Figs. 5, 8). Based on the patterns of the blocks identified through mapping (Fig. 3A) and field observations made at different stratigraphic levels, it can be concluded that the former are somehow uniformly scattered throughout the whole pile of the formation. From a compositional point of view however, there is a certain gradation and greater occurrence of blocks belonging to the PPBC units (specially Los Caños Fm and the Imbert Fm) closer to the contact with the basement complex which suggest that these may therefore be considered true olistoliths. On the other hand, the abundance through the whole pile of hectometer or even larger size blocks of both carbonate and siliciclastic nature from unknown sedimentary units becomes relevant, as these are also interpreted as olistoliths. It is important to note that our mapping showed no blocks of the Luperón Fm and Villa Trina Fm embedded within the San Marcos Fm., thus refuting the conclusion by Pindell and Draper (1991) that very recent (diapiric) emplacement of the San Marcos Fm had taken place. Nevertheless, new mapping has proven the existence of recent, anomalous contacts of the San Marcos Fm, for example those overlying the Luperón Fm (Fig. 3B, geological cross section II). It is believed that these can be better explained to be a result of particularly unstable rheologic behavior driven by the internal flow of such a thick, expansive clay bearing unit, suggesting a post-emplacement sort of mud diapir-type movement; the same mechanism has been documented in several accretionary complexes (e. g., Barber and Brown, 1988; Brown and Westbrook, 1988; Camerlenghi and Pini, 2009; Orange, 1990 and references therein).

As in the case of the Serpentinite Breccias unit, there is a clear preferential distribution of metamorphic blocks close to the trace of the Camú fault. Therefore, it is once again in the outcrops closer to the town of Imbert where the San Marcos Fm shows the highest content of metamorphic blocks with very similar composition and grade (including high-P blocks) to the ones identified in the Serpentinite Breccias unit, thus contributing to the perception that both units have undergone a certain degree of mixing between them.

According to the composition of bearing blocks (many of which derive from the PPBC units and Imbert Fm), cartographic patterns and stratigraphic position (i.e. unconformably overlying the PPBC and unconformably overlain by the Luperón Fm) sedimentation or emplacement of San Marcos Fm is considered to be most probably Eocene in age. The aforementioned new dating information obtained from foraminifera associations found in an autochthonous bioclastic level specifically suggests that these sediments are of Middle Eocene age.

4. Discussion. Significance of the Serpentinite Breccias unit and San Marcos Fm in the context of subduction and collisional processes

The Serpentinite Breccias and the San Marcos Fm are regionally outcropping units involved in collisional processes between North

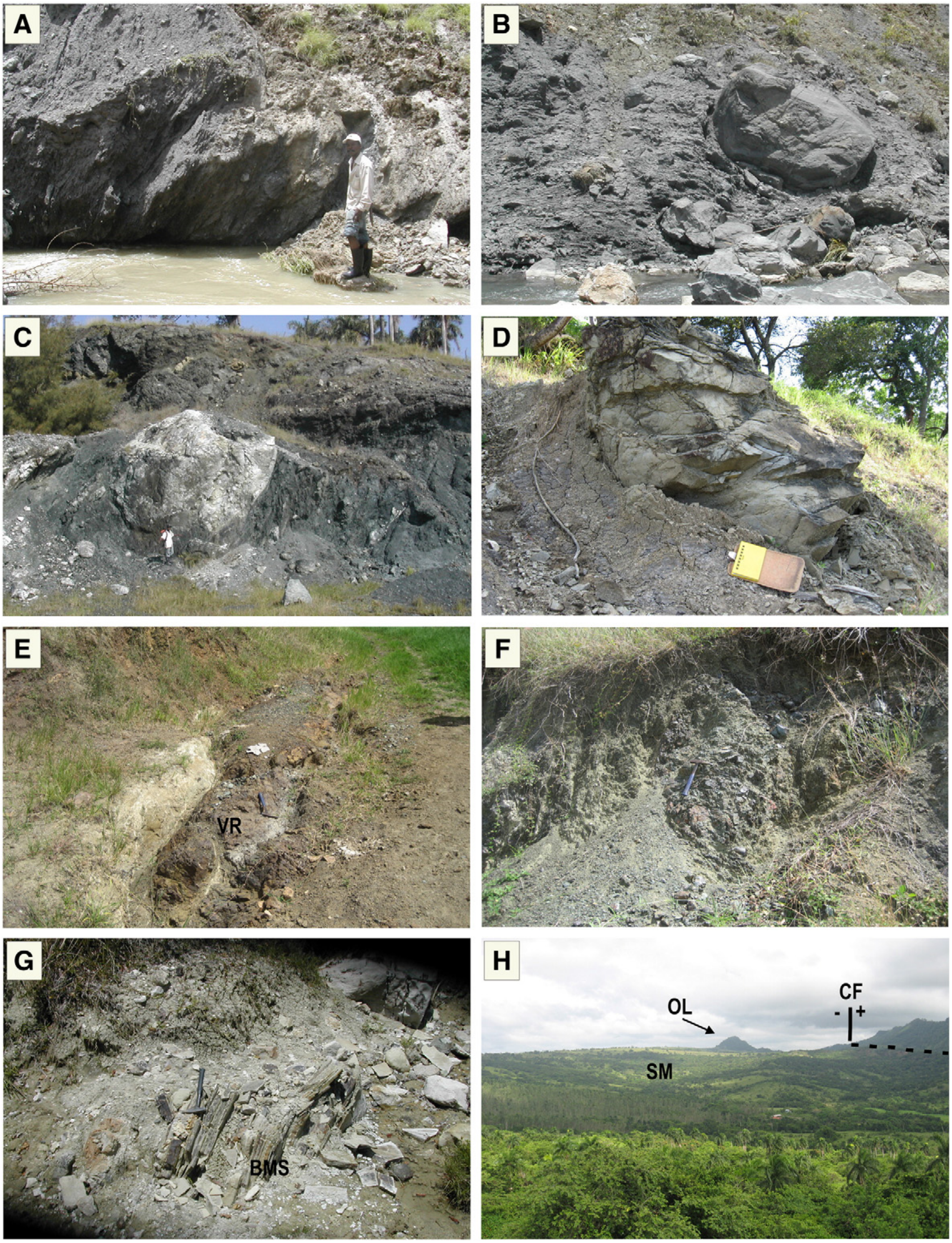

Fig. 8. Photographs of the San Marcos Fm in the Puerto Plata area: (A) Most common facies of San Marcos Fm: scaly, clay-abundant matrix embedding blocks of different sedimentary lithologies (limestones and sandstones) and sizes; San Marcos river near the locality of San Marcos Arriba (SW of Puerto Plata) B) The same facies as in (A), in this case including a 2 × 2 m size block of feldspathic sandstones of unknown origin; Camú river section near the locality of Juan de Nina; (C) Thick interval or body of serpentinite breccias interbedded within the San Marcos Fm, south of the town of Puerto Plata; the photograph shows a 5 × 5 m block of unknown volcanic (probably basalt) rocks embedded in a serpentinized brecciated and schistose matrix containing other smaller blocks of diverse lithologies. (D) Disrupted block of convoluted (autochthonous?) sandstones included in an abundant clayey (slightly schistose) matrix, near Barba Rucia village; (E) Meter scale block of volcanic rocks (VR) (most probably from Los Caños Fm) included in San Marcos Fm, near Loma Las Bestias village; (F) Meter-scale body of serpentinite breccias included in San Marcos Fm in the same locality as the previous photograph; (G) Beds of laminated bioclastic marly sandstones (BMS) of San Marcos Fm dated by foraminifera as Middle Eocene; outcrop located near the village of El Café; (H) Panoramic view of the characteristic equilibrium profile of the San Marcos Fm, north (left) of Camú fault (CF); + symbol indicates fault block moving inwards); the isolated small mountain in the middle of the photograph corresponds to a kilometer size olistolith (OL) of unknown limestones.

American and Caribbean plates. In the past, several options regarding the mode of emplacement of these units have been suggested (i.e. olistostrome, tectonic mélange, exhumed, subduction-related regional-scale mélange, mud diapir, etc.; Bourgois et al., 1982, 1983; Bowin and Nagle, 1982; Eberle et al., 1982; Krebs et al., 2008; Nagle, 1966, 1974, 1979; Pindell, 1985; Pindell and Draper, 1991; Saumur et al., 2010).

Based on the observations made during this study, it is considered that the concept of olistostrome best defines or fits the lithological characteristics of the San Marcos Fm, which is observed to behave as a chaotic, internally disrupted and incoherent mass displaying recognizable sedimentary features. The San Marcos Fm contains centimeter to kilometer-scale blocks (olistoliths) of known or exotic origin (intra or extra-basinal) embbeded in a dense, schistose clayey (scaly clay) matrix deposited by syntectonic subaqueous mass-transport processes. The olistoliths may be incorporated into this process in a semiconsolidated (pore water rich) state, whereby both the olistoliths themselves and the hosting formation undergo deformation in a soft-sediment manner. The cartographic pattern of both the San Marcos Fm and the accompanying Serpentinite Breccias unit surrounding or within the PPBC, coupled with the presence of blocks deriving from the units making up this complex (serpentinites, gabbros, Los Caños Fm and even La Isla Limestone) in addition to blocks from the Imbert Fm (among others) contained therein unequivocally suggest that deposition took place very near to and within the PPBC, thereby slightly postdating the Imbert Fm.

The models proposed in the cartoons showed in Fig. 9 attempt to portray a paleogeographic (or paleotectonic) reconstruction of the final stages of subduction and the collisional process that followed, in order to show the relationship among all geological units present nowadays in the Puerto Plata area, especially those associated with mélange units. The purpose of these models is to show the genetic and spatial relationships among mélange and other units outcropping in the area, in order to illustrate a possible end-of subduction and collisional processes scenario. To this end, only a tentative palinspastic reconstruction has been made, mainly by unraveling the post-Eocene Camú fault sinistral movement. In addition, these models present two conceptual sketches that summarize and interpret the cartographical, lithological, tectonic, and geochemical features of these units.

Fig. 9A, shows the scenario corresponding to the final stages of subduction and arc volcanism in Early Eocene (Ypresian) times when reworked material coming the early (and incipiently) exhumed Jagua Clara mélange and/or Río San Juan accreted complex is deposited in the corresponding trench. This is consistent with the rank of cooling ages (73.2 to 62.1 Ma) obtained by Krebs et al. (2008) for high-P blocks in the Jagua Clara mélange, which marks the timing of the onset of exhumation processes in the subduction channel, prior to its further exposure at surface. $^{40}Ar/^{39}Ar$ (on hornblende) plateau ages (SYSMIN Project, unpublished data) obtained in the volcanic arc complexes located south of the Camú fault (Pedro García and Palma Picada complexes; Figs. 1 and 2) cluster between 50.44 $\pm$0.85 and 46.30 + 2.40 Ma (Table 1) that is in agreement with the time about when volcanism end. This is also the main timeframe during which deposition of the Imbert Fm is thought to have taken place. The association of breccias, debris, turbiditic volcanogenic sandstones and radiolarian-rich laminated siliceous tuffites found in this formation suggest a deep-sited marine environment with a remnant volcanic activity and important coeval tectonism. Thus, it is believed that deposition of the Imbert Fm might have taken place in the outer(-most?) part of the forearc basin or also in the inner trench wall as the first foreland deposits involved in the ongoing deformation. Similar locations have been proposed by Bowin and Nagle (1982) and Pindell and Draper (1991), the PPBC being in either case the main underlying substratum (with a proven island arc geochemical affinity). This environment was also allocating debris of serpentinites and occasional fragments of metamorphic rocks most probably originating from uplifting and initial exhumation of the nearby accretionary prism (Río San Juan complex). Consequently, it is inferred that the PPBC should be located relatively close to the RSJC, probably in the leading edge of the frontal arc (partially covered by the forearc basin deposits) and ahead of the active volcanic arc proper, represented by the Palma Picada and Pedro García complexes.

The most reliable $^{40}Ar/^{39}Ar$ (on hornblende; plateau) dating obtained in Los Caños Fm (SYSMIN Project, unpublished data) has given a Late Cretaceous (81.60 $\pm$ 2.70 Ma; Campanian) age (Table. 1), suggesting that during Early Eocene times the bulk of arc volcanism was already inactive in the PPBC and thus, this complex might have been already (tectonically) included in the shallower (non metamorphic) part of the accretionary wedge as the northernmost outcropping fragment of the Caribbean plate in this transect. Therefore, in spite of their apparent lithological similarities in terms of mélange-type units that include high-P exotic rocks, care should be exercised when directly correlating these two complexes. It is not known whether Río San Juan complex rocks (or equivalent units) may be attached to the offshore prism underneath the PPBC. In any case, the accretionary wedge in this western segment of Cordillera Septentrional shows a high degree of involvement of frontal arc units in comparison with the low sediment supply that is confined to a narrow band located offshore (Dolan et al., 1998).

In this context, a certain portion of the Serpentinite Breccias unit is interpreted to represent the product of sedimentary recycling of subduction channel related mélange(s) identified in the Río San Juan complex (Jagua Clara mélange, Krebs et al., 2008), which is a plausible source area for the facies of this unit that bear metamorphic and high-P rocks. It is deduced that another significant part of the unit that is closer to the PPCB and contains blocks belonging to it results from the erosion of peridotitic bodies (most probably) tectonically emplaced by thrusting and folding within this complex. La Isla limestone, which supposedly originally overlaid the PPBC and other carbonates located above the Río San Juan complex is envisaged in the model as shallow marine deposits linked to the ephemeral development of isolated carbonate (occasionally reefal) platforms.

Fig. 9B depicts the moment of the collisional event between the North American and Caribbean Plates triggered by the full arrival of the Bahamas carbonate platform into the subduction channel (Draper et al., 1994; Pérez-Estaún et al., 2007; Pindell and Barrett, 1990). Based on metamorphic P-T data and related isotopic age determinations, and assuming average subducting rates for the Caribbean region, Escuder-Viruete et al (2011) have quantified that the high-P rocks of Santa Bárbara Marbles and El Rincón Schists structural units of the Samaná complex (which are considered to make up the bulk of the subducted Bahamas carbonate platform) began to subduct between about 46 (Early Eocene) and 36 Ma (Late Eocene) respectively. Rough estimations of the onset of subduction of Punta Balandra nappe rocks, which have been identified to associate with the most distal part of this platform, suggest an age of about 65.3 Ma (Maastrichtian–Paleocene boundary). Similarly, based on retrograde P-T paths and $^{40}Ar/^{39}Ar$ cooling ages (between 38 and 33 Ma) of Punta Balandra nappe high-P rocks, these authors have established that the beginning of accretion of this nappe to the overriding collisional accretionary wedge occurred around Late Eocene times, thus marking the end of subduction processes and the subsequent propagation of the Samaná deformation front to the foreland.

The available data used in this work suggest a Middle Eocene (Lutetian) age for this event in the Puerto Plata area. Other authors (Goncalves et al., 2000; Iturralde-Vinent et al., 2008; Mann et al., 1991; van Hinsbergen et al., 2009) propose a similar age for this collisional event between the North American and Caribbean plates. The first consequence thereof is the complete extinction of any remnant volcanic activity in the Cordillera Septentrional island arc complexes, as evidenced by geochronological data which indicates that the most recent age of volcanism in the region (and particularly, south of Camu fault) is Lutetian (Table 1); the second consequence is the settlement of a shallow carbonate platform of Middle and Late Eocene age (upper deposits of Hidalgos Fm and other unnamed equivalent units) on the volcanic and volcano-sedimentary rocks probably related to regional uplift resulting from the collision effect (Harris et al., 2009). Part of the accretionary complex is exhumed, arising as the source area and

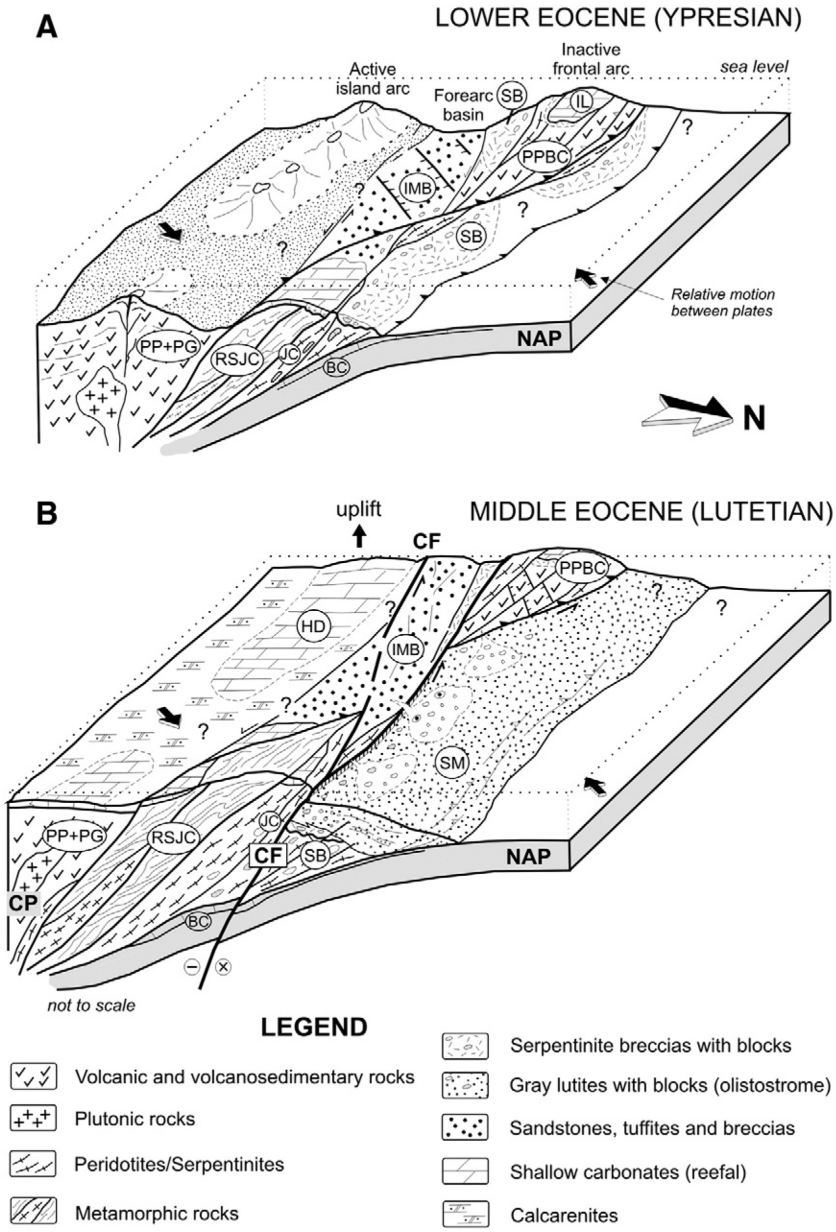

Fig. 9. Cartoon models depicting an approximate reconstruction of end of (oblique) subduction and subsequent collisional scenario between North American and Caribbean Plates, showing the inferred area of deposition or emplacement of mélange-type units and their relationships with other units of the Puerto Plata and (neighboring) areas; for the reconstruction, the post-Eocene strike-slip movement of the Camú fault has been unraveled: (A) Early Eocene (Ypresian) times: final stages of subduction setting just prior to the onset of collision and complete extinction of island arc volcanism, showing the position of the Caribbean (active) island arc, (inactive) frontal arc and forearc basin, and the deposition of the Serpentinite Breccias unit by sedimentary reworking above the early exhumed (subduction channel) Jagua Clara mélange (JC) and Río San Juan accretionary complex (RSJC) (B). Middle Eocene (Lutetian) times: collisional event and main stage of accretionary wedge exhumation as the context for the deposition of San Marcos olistostrome. See text for explanation. RSJC: Río San Juan basement complex; JC: Jagua Clara mélange; PPBC: Puerto Plata basement complex; PP + PG: Palma Picada and Pedro García (island arc) basement complexes; IMB: Imbert Fm; HD: Los Hidalgos Fm; IL: La Isla Limestone; SB: Serpentinite Breccias; SM: San Marcos Fm; CF: Camú fault zone; BC: Bahamiam carbonate platform; NAP: North American Plate. CP: Caribbean Plate.

uplifted scenario hosting the development of gravitationally-driven processes; as a consequence, the San Marcos olistostrome is so deposited in an adjacent trench located in a frontal (or overlying) position with respect to the exhumed Jagua Clara mélange of the RSJC. At this time, the obliquity of collision produces the initial strike-slip movements of the Camú fault that will accommodate most of the left lateral relative movements in this area after the blocking of the subduction zone, as oblique convergence continues. This fault marks the southern extension of the PPBC and related rocks (including the Imbert Fm), and its movement results in their uplift, deformation and internal disruption (by localized transtension-related normal faulting?), favoring the incorporation of these units into the San Marcos Fm as blocks and olistoliths or serpentinite brecciated intervals or bodies.

Additionally, the control exerted on the internal distribution of high-P metamorphic exotic blocks (i.e. knockers; Karig, 1980) within this formation and the Serpentinite Breccias unit becomes evident. The most immediate provenance of such rocks may be located in the Río San Juan complex, where they are included in exhumed subduction channel related mélanges (Krebs et al., 2008). The process that drives the feeding of these knockers into both the San Marcos Fm and the Serpentinite Breccias unit remains unknown, but it is most likely related with serpentinization and exhumation processes taking place in the subduction channel (Federico et al., 2009; Schwartz et al., 2001).

Examples of olistostromes displaying features that closely resemble those of the San Marcos Fm, are widely described in subduction contexts around the world (e.g. Lucente and Pini, 2003; Moore et al, 1976; Platt, 1986; Torelli et al., 1997) and have been recently interpreted as massive mass-wasting events produced in the frontal part of an accretionary complex (e.g. Makran accretionary complex, Burg et al., 2008) or Alpine 'forearc' context (Cavazza and Barone, 2010; Lucente and Pini;, 2003) near Hispaniola, in Cuba (Iturralde-Vinent et al., 2008). Thus, sedimentary reworking of these mélanges can be a usual mechanism that may explain the occurrence of this type of deposits in a collisional arc-continent context. Another point of view is provided by Fryer et al. (1999, 2000), who has documented the fault controlled extrusion of serpentinite-dominated mud diapirs bearing metamorphosed (blueschist) rocks in the frontal (forearc) part of the non-accretionary Mariana convergent plate margin, from the upper decollement surface of the subduction zone located at depths as great as 25 km. Taking into account the foregoing description and definition of the San Marcos Fm, the latter is not believed to be, in its entirety, a mud diapir as proposed by Pindell (1985) and Pindell and Draper (1991). However, it is possible that some of the serpentinite muds or breccias found within or associated with the San Marcos Fm near the Camú fault trace have this origin, suggesting that all or most of the high-P exotic blocks were carried to the surface during the upward movement, and subsequently and immediately subject to sedimentary rework at the surface.

Regional evidences suggest that the impact of this collisional event was immediate throughout most of the arc edifice, even at considerable distances from the collisional front. These include the uplift and southward thrusting of the Tireo island arc domain of SW Cordillera Central over the nearby Peralta (back arc) basin, and the syntectonic deposition of the Ocoa Fm, which represents another well known chaotic unit outcropping along the southern slopes of this range (Hernaiz Huerta, 2000, 2006; Hernaiz Huerta and Pérez-Estaún, 2002; Heubeck, 1988; Heubeck and Mann, 1991). The Ocoa Fm is a 8000 m thick, pelitic and conglomeratic olistostromic-type unit deposited over a very short time span during late Eocene (and possibly Early Oligocene) times in a NW-SE direction, adjacent to the Tireo frontal thrust (San José-Restauración fault zone; Fig. 1) and resting unconfomably while dramatically eroding (>3000 m) the underlying Peralta Group sequence (Dolan et al., 1991; Heubeck, 1988; Heubeck et al., 1991). The most chaotic facies of this unit incorporate abundant olistoliths of older and neighboring formations, some of which are up to 16 km long and 1.5 km thick (Hernaiz Huerta, 2000). It may be concluded then that (at least some of) the most important mélange and olistostromic-type units of Hispaniola seem to be linked to a contemporary, short-lived episode related to the collision event.

Lastly, the intense strike-slip tectonic superimposed on the whole region over a long period, spanning (at least) from Paleogene times until present day (i.e., Dolan and Mann, 1998), has severely transposed the original relationships among all these units, making a complete reliable reconstruction of the geological history difficult. Nevertheless, the overall information presented in this paper, which is based mainly on fieldwork and is supported by geochemical, petrological and geochronological data, shows the validity of conducting integral studies aimed at acquiring and expanding the knowledge that surrounds such complex geological contexts.

5. Conclusions

Mélange-type units outcropping in the Puerto Plata area of the northern Dominican Republic have been mapped in a regional-scale geological survey carried out in the Cordillera Septentrional, and are described and interpreted in this paper as geological units that record the end of subduction and collisional processes taking place in an oblique convergent regime between North American and Caribbean plates during Eocene times. These units are the San Marcos olisthostrome and a Serpentinite Breccias unit that have been identified and mapped for the first time in this area as a distinct lithostratigraphic and mappable unit located at the base and interbedded within the lower stratigraphic and structural section of the former. Both formations outcrop unconformably and overlie the Puerto Plata basement complex (inside or around it), now with a proven island arc geochemical affinity, and typically incorporate blocks of all sizes, ranging from small fragments to olistoliths that derive mainly from this basement complex and from the overlying Imbert Fm that makes up the sedimentary cover. In addition, they also comprehend a great deal of blocks belonging to undetermined sedimentary and metamorphic units that include high-P rocks.

New information obtained from 1:50.000 scale mapping and other accompanying sedimentary, biostratigraphic, petrological, geochemical and radiometric data has allowed to reinterpret, discuss and clarify previous detailed surveys that were carried out (i.e. Nagle, 1979; Pindell and Draper, 1991), taking a next step forward in the acquisition and expansion of knowledge surrounding the regional geology of this area. The sedimentary features that have been clearly recognized in (most of) the outcrops of the Serpentinite Breccias unit indicate extensive sedimentary recycling of peridotite and serpentinite massive bodies or subduction related mélanges; these last ones are suspected to have reached the surface at an early stage of the Río San Juan accretionary complex exhumation (Early Eocene), coevally with the latter stages of island-arc volcanism. The exhumation process triggered the exit of high-P exotic rocks derived from the subducting channel and probably, in combination with strike-slip tectonics, such process also helped expose these high-P rocks at the surface and their final reworking into the Serpentinite Breccias unit and even into Imbert Fm forearc deposits. The San Marcos Fm, slightly younger in age but mixed with the Serpentinite Breccias unit in its lower part, records the collisional event and the main exhumation stage (Middle Eocene) of the Río San Juan accreted complex and displays the typical features present in olistostromes and other mass-wasting deposits recognized in extensive areas of forearc and accretionary complexes involved in arc-continent collisional processes. Therefore, in spite of their apparent similar high-P rock content embedded in chaotic, mélange-type formations, no obvious correlation exists between the Río San Juan and Puerto Plata basement complexes, as proposed by a number of previous studies. The results herein provided demonstrate that the Jagua Clara mélange of RSJC is an *in situ* exhumed subduction channel mélange whereas the Serpentinite Breccias and the San Marcos are clear chaotic sedimentary formations partially derived from the depositional reworking of the former.

Once Caribbean arc volcanism became extinct, a regional uplift of the whole area followed the emplacement of the San Marcos olistostrome, imposed by the onset of an intense left-lateral transpressional regime that remains active until today.

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